BORDLINE® M

A very high-efficiency AC/DC/DC converter architecture for traction auxiliary services

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The power needs on a train are manifold. The traction itself requires power, but so do many auxiliary consumers ranging from traction excitation, to on-board lighting, heating and air conditioning. Space and cost constraints are increasingly leading to demands for a single converter able to cover all these needs. Such a converter must supply both AC and DC outputs. Its output is required to meet high standards, it must nevertheless deal with a wide range and quality of input power conditions.

***ABB Review* takes a look at some of the technologies behind the company's BORDLINE® M series of converters and some of the challenges involved in its design.**

Sustainability and energy

The new generation of traction power supplies must not only meet load-characteristic demands, but also be able to process large amounts of energy (due to the increasing number of loads, caused for example, by rising demands on on-train comfort) and must do this with very high efficiency, reliability and power density. Moreover, cost is a very important factor. In high power-density building block converters, it is usually necessary to operate semiconductor devices at high switching frequencies. The downside of this is that increased switching frequencies bring with them higher switching losses. In switch-mode PWM (pulse width modulation) power supplies, the switching losses can be so high that they make the operation of the system at very high frequencies unfeasible, even when soft-switching techniques are used.

Resonant-mode power supplies[1)] address all the aforementioned issues through their lower switching losses [1]. The use of such architectures represents an interesting option to those applications requiring the performance enhancements outlined above.

In today's traction applications, insulated-gate bipolar transistors (IGBTs) are the most suitable switching devices for meeting the voltage and current requirements and also feature very high insulation voltage levels. For those devices operating at high switching frequencies, zero-voltage switching (ZVS) can be a valuable option to enhance the converter efficiency. This approach reduces to zero the switching energy associated with both the high parasitic capacitance values characterizing the modules (affecting the turn-on losses) and the reverse recovery of anti-parallel diodes (associated with their turn-off).

For a nominal input voltage of 1,000 Vrms AC, the corresponding operating range varies between 700 Vrms and 1,200 Vrms.

One of the biggest challenges facing designers of power supplies for traction applications is the extremely wide input-voltage range at the converter input terminals. This variance should not have any effect on the overall system performances and efficiency during all the different operating conditions. The possible input voltage variation range for all possible electric traction systems are shown in 1. For a nominal input voltage of 1,000 Vrms AC, the corresponding operating range varies between 700 Vrms and 1,200 Vrms – a very large range.

Although several papers have been published on the topic of wide input-voltage compensation methods for power supplies, not so many can be found on how to deal with such broadly varying operating conditions.

For an extreme input voltage variation as shown in 1, the converter optimization design remains a concern wherever resonant topologies are used. As a matter of fact, the wide input voltage range might result in high levels of circulating energy. This reduces the overall efficiency considerably, and also the converter power density.

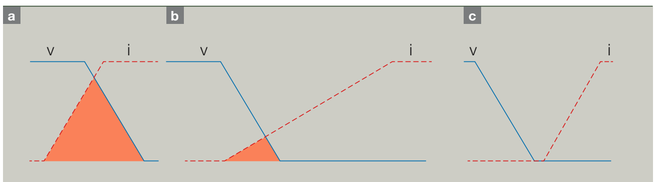
In today's traction applications, IGBTs are the most suitable switching devices for meeting the voltage and current requirements and also feature very high insulation voltage levels.

Several solutions have been proposed in the past attempting to meet these requirements and also the output load variations. The conventional series-resonant converter operates with ZVS for the active devices when the switching frequency is above the resonant frequency. However, for wide

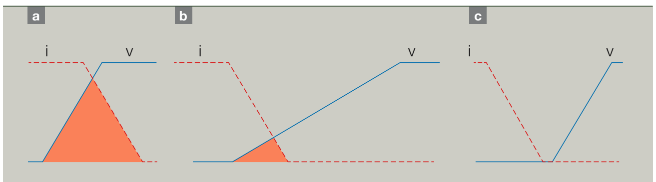
1 Line input voltage range for railway systems, from the EN50163 international standard. The broad input range creates special challenges.

EN50163, UIC550					
System voltage	Minimum not permanent	Minimum permanent voltage	Normal voltage	Maximum permanent voltage	Maximum not permanent
	Voltage Umin2 (V)	Umin1 (V)	Unom (V)	Umax1 (V)	Voltage Umax2 (V)
DC system	400	400	600	720	800
	500	500	750	900	1,000
	1,000 (900UIC 10 min)	1,000	1,500	1,800	1,950
	2,000 (1,800 UIC 10 min)	2,000	3,000	3,600	3,900
AC system	700 Vrms	800 Vrms	1,000 Vrms 16,67 Hz/50 Hz	1,150 Vrms	1,200 Vrms
	1,050 Vrms	1,140 Vrms	1,500 Vrms 50 Hz	1,650 Vrms	1,740 Vrms

2 Turn-on commutation mode: hard a, L in series b, soft c



3 Turn-off commutation mode: hard a, L in series b, soft c



Footnote

1) As their name suggests, resonant-mode circuits use resonance effects to support them in forming their AC output.

variations of the input voltage and output load, the converter must operate with wide switching-frequency variations. This complicates the optimization of the converter [2,3].

Furthermore, in the case of high input voltages, as found in railway applications, the necessity to use devices with high-voltage-ratings aggravates the problem. The series connection of converters has been proposed to reduce the voltage stress across the main devices [4,5]. This permits the use of devices with a low-voltage rating, while maintaining the switching characteristic of the converters. However, an additional control strategy is needed to balance the input voltage across the input capacitors.

Setting out to minimize the complexity of the various approaches, the BORDLINE® M series converter presents a novel solution to mitigate the impact of a wide-input voltage range in the performance of AC/DC/DC isolated converters for traction auxiliary services. The units generate a galvanically isolated, constant direct voltage for charging batteries, as well as a sinusoidal three-phase voltage to drive AC motors. Optionally, the sinusoidal output voltage can be galvanically isolated. Here, the front-end power architecture is a three-level PFC (power factor corrector) converter, which follows the input voltage variations, guaranteeing a power factor close to unity under all operating conditions. The second converter stage is realized by means of a three-level LLC[2] isolated resonant converter operated in ZVS and quasi ZCS (zero current switching) mode.

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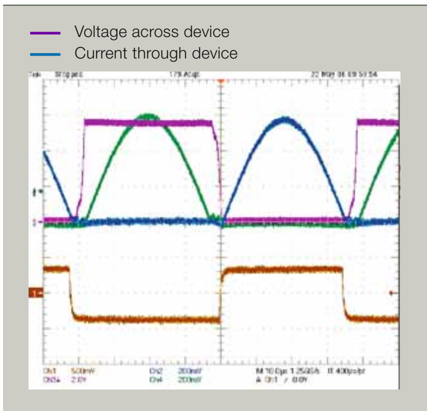
Hard switching versus soft switching

The commutation mode of semiconductor devices is usually classified as hard-switched, snubbered or soft-switched depending on the quantity of energy losses generated during the state transitions (turn-on or turn-off).

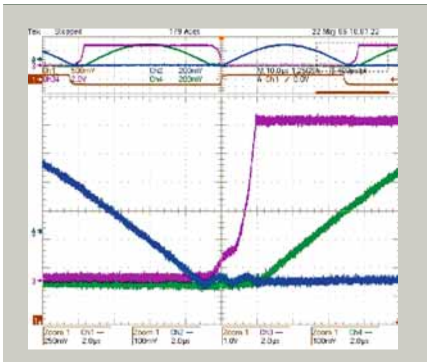
2 shows these three commutation modes. In hard switching 2a, there is a considerable area of overlap between the voltage across the semiconductor device and its commutated current. 2b illustrates the typical commutation of a device with an L (inductor)-type snubber circuit in series with the semiconductor: The snubber circuit reduces the current's rate of change (dI/dt) and this helps reduce the overlap between the voltage and the current, significantly reducing the switching losses. 2c shows a typical soft-switched commutation (ZVS, zero-voltage switching). An external circuit is used to practically eliminate the overlap. The semiconductor does not start conducting until the voltage across its terminals has already reached zero. Turn-on losses are thus eliminated.

4 Soft-switching behavior of a 1,700V IGBT with ZVS and ZCS:

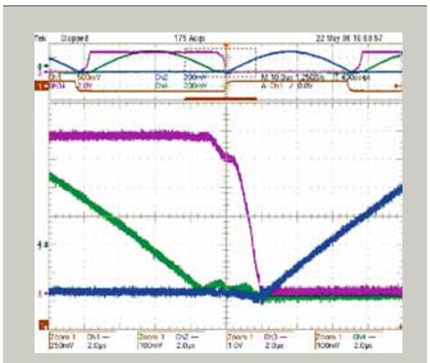
a Switching cycle



b Turn-off transition with ZCS



c Turn-on transition with ZVS



Footnote

[2] An LLC is a resonant circuit using a capacitor and two inductances; Both of them could be the winding parameters of the transformer.

The turn-off transition 3 is comparable. The hard turn-off 3a generates the greatest losses. The snubbered mode 3b is achieved by means of a C (capacitor)-type snubber connected in parallel to the device, reducing the device dV/dt. Finally, 3c shows the soft-switched turn-off transition (ZCS, zero-current switching).

A soft-switched turn-on/turn-off transition for an IGBT device is shown in 4.

AC/DC/DC topology description

The block schematic of the BORDLINE M series power architecture, presented in 5, combines high performances with high reliability while reducing costs. Here both PWM and resonant technologies were adopted so that high conversion efficiency could be achieved under all operating conditions.

> One of the biggest challenges facing designers of power supplies for traction applications is the extremely wide input-voltage range at the converter input terminals.

The first converter stage is realized by means of a direct AC/DC step-up converter working in PWM hard-switching mode, while the second DC/DC isolated stage is realized as a three-level half-bridge configuration and works in LLC resonant mode. On account of the resonant technology, the second converter stage is able to guarantee zero-voltage switching (ZVS) and quasi zero-current switching (ZCS) in all operating conditions, hence significantly reducing the switching losses in the silicon devices. In the third stage, an output three-phase inverter and a DC/DC battery charger are connected to the secondary DC-Link.

Three-level PFC boost converter

The three-level PFC boost converter operating in hard-switching mode receives a variable input voltage (in this case study, between 700 Vrms and 1,300 Vrms). Using duty-cycle modulation, a constant voltage is produced at the output terminals. This feeds the second resonant stage, always guaranteeing an input-line current that is sinusoidal and in phase with the line voltage. The three-level PFC boost converter is realized by means of an input diode-bridge rectifier and a three-level DC/DC converter. A boost inductor (Ls) is used to store the line energy for the boosting action, while an input EMI (electromagnetic interference) filter is needed to meet all the current harmonics injection standards.

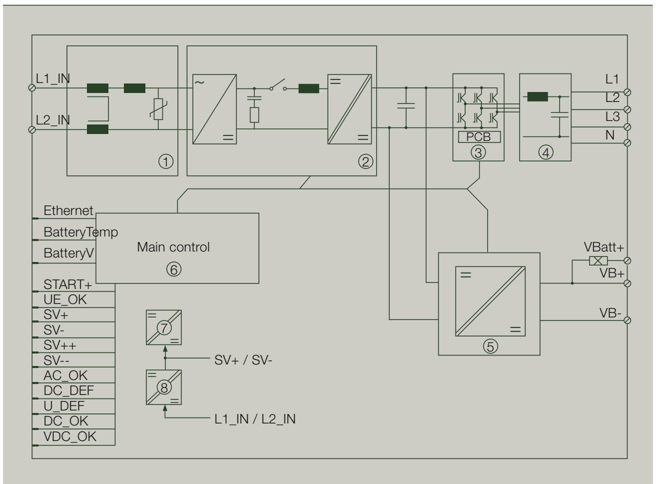
The IGBT switching frequency has been set low in order to limit semiconductor losses. Using the possibility of interleaving the firing signals sent to the semiconductors on the three-level boost converter (by 180° with respect to the switching period), the equivalent switching frequency for the entire five-level converter as seen by the network is higher than 6.5 kHz. Thanks to this equivalent increase of the switching frequency, it is possible to reduce the size of both the boost inductor (which is a quarter the size of that for a conventional two-level boost converter) and the EMI input filter, whose size is defined by the level of harmonic-current mitigation required by standards.

> By implementing an active compensation it is possible to mitigate all the problems connected to the undesired harmonics.

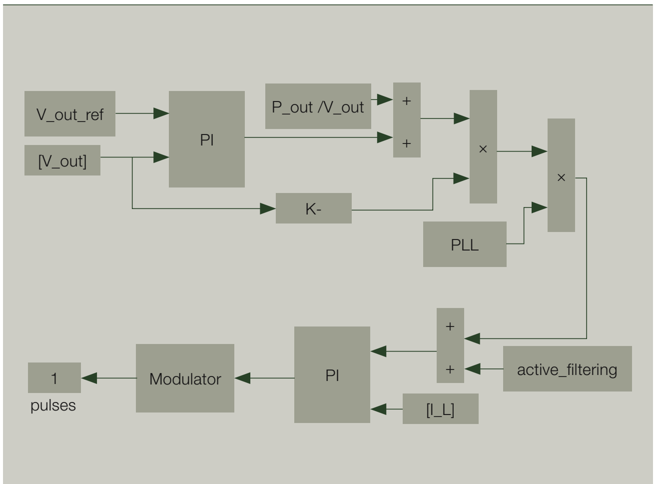
PFC converter control

The control system makes use of standard PI regulators 6. A standard cascaded control scheme guarantees, by means of an "outer and slower" loop, the desired output DC-link voltage regulation, and, by means of an "inner and faster" loop, a boost inductor current control. This permits the required high power factor to be achieved on the line side. The line-voltage synchronization (PLL), needed for the inner current control, is realized immediately after the input diode bridge. A duty-cycle reference signal (sinusoidal reference) is then compared to two triangular carriers (whose frequencies are equal to the desired devices' switching frequency), so that two interleaved firing signals can be obtained for the three-level boost converter devices. Two additional feed-

5 Converter layout

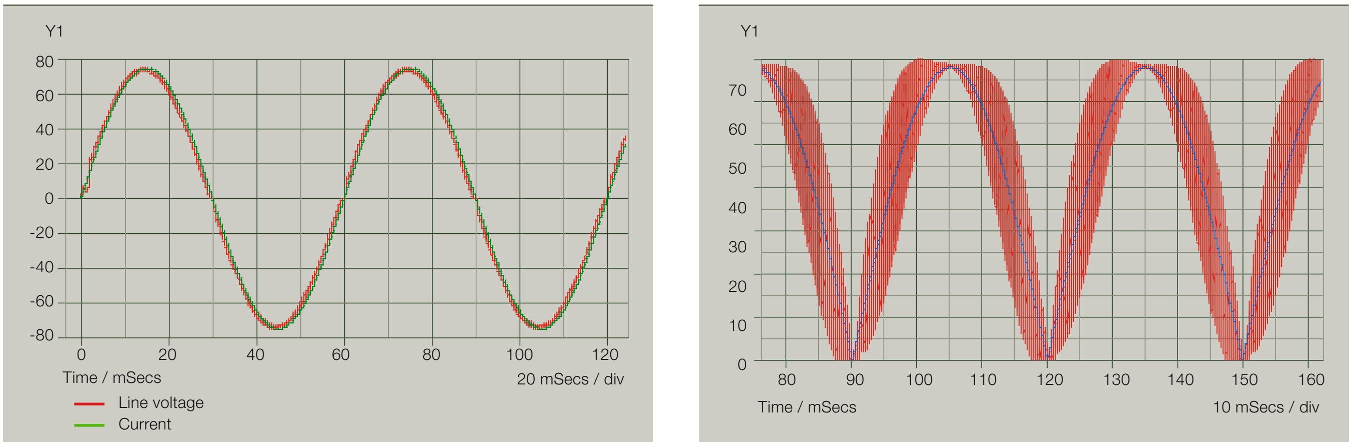


6 Block diagram of the power factor correction (PFC) control strategy



7 PFC simulation results at nominal output power and voltage

a Line voltage and current | b Boost converter current and its reference



forward actions (one on the reference current and one on the reference line frequency) enable faster time responses during control to achieve a steady-state operating mode.

The increased equivalent switching frequency makes it possible to reduce the size of both the boost inductor and the EMI input filter.

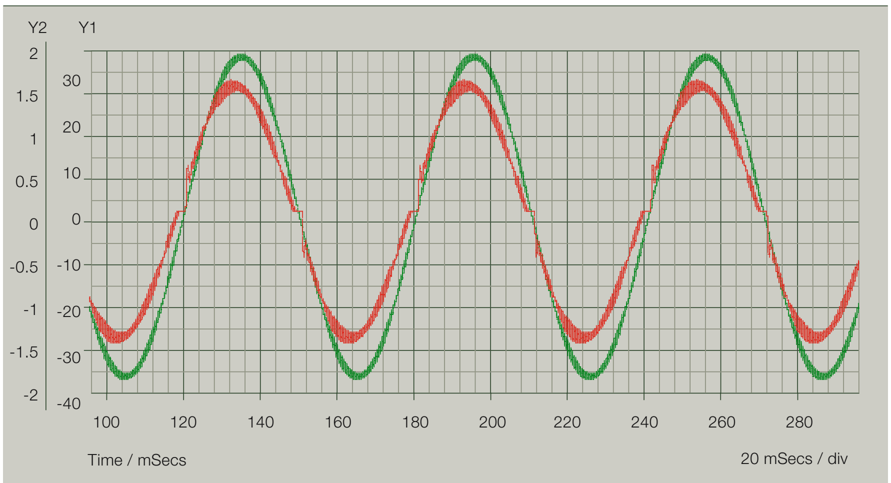
Simulations were performed under the following conditions: 50 kW output power, 700 Vrms input voltage and 2,000 V DC-link set-point voltage 7. The implemented control scheme shows quite good behavior for all the load conditions in the whole input voltage range, also at light load conditions (output power less than 20 percent of the rated power) and high-input voltage (higher than 1,200 Vrms). Under these conditions, the line currents usually present quite a high level of harmonic distortion, but by implementing an active compensation of the undesired harmonics it is possible to mitigate all the problems connected to the undesired harmonics and be fully compliant to the international standards of electromagnetic pollution on railway networks. The line current is sensed (it can also be the current of the boost inductor, with the switching frequency harmonic properly filtered), and this value is added to the reference sinusoidal current that theoretically should circulate in the network. This modified reference signal is then compared with the actual boost current and processed by a PI controller. 8 compares the compensated line current with the line voltage.

On account of the resonant technology, the second converter stage is able to guarantee zero-voltage switching (ZVS) and quasi zero-current switching (ZCS) in all operating conditions.

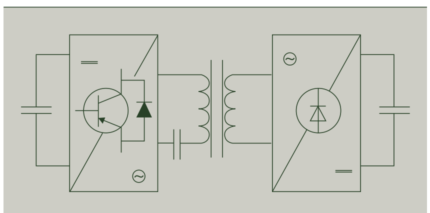
Isolated three-level half bridge

The resonant converter stage implementing the galvanic isolation 9 consists of several elements; an input DC/AC three-level front end converter (receiving a stabilized DC voltage); a resonant circuit with three passive elements (implemented with external resonant capacitors and parasitic impedances of the transformer); a galvanically isolated transformer of the desired turns ratio in order to guarantee a proper output DC-voltage; and an output diode bridge rectifying the transformer output voltage.

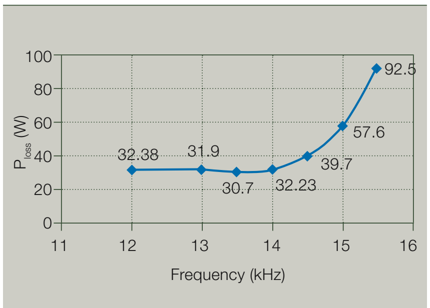
8 PFC simulation results at light load conditions (30 percent output power) and high-input voltage (1,300 Vrms)



9 Block schematic of the implemented second converter stage

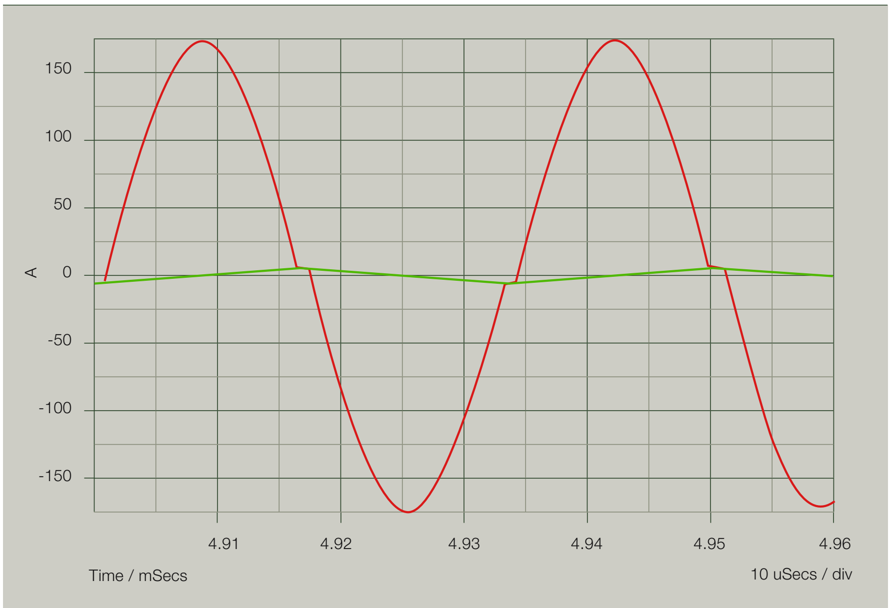


10 Mean losses of resonant converter IGBT per cycle versus resonant tank frequency (due to component tolerances)



The resonant tank circuit is designed so that the devices of the DC/AC three-level front-end converter are operated under ZVS and almost in ZCS due to the very small current needing to be turned off. Actually, the ZVS mode guarantees zero turn-on losses for all of the four active devices, and zero reverse recovery for all the associated free-wheeling diodes. Furthermore, the three-element resonant tank allows the diode bridge rectifier (at the output of the transformer) to be operated under zero-reverse recovery energy, while the low harmonic content resonant tank current allows strong reduction of the passive components losses 11. In summary, all the switching losses of the second converter stage are basically reduced to zero, highly enhancing the overall converter efficiency.

11 Resonant tank current at nominal load



12 The new BORDLINE® M-series

Thanks to the effect of the transformer magnetizing inductance, the converter behavior is insensitive to load or system-parameter variations.

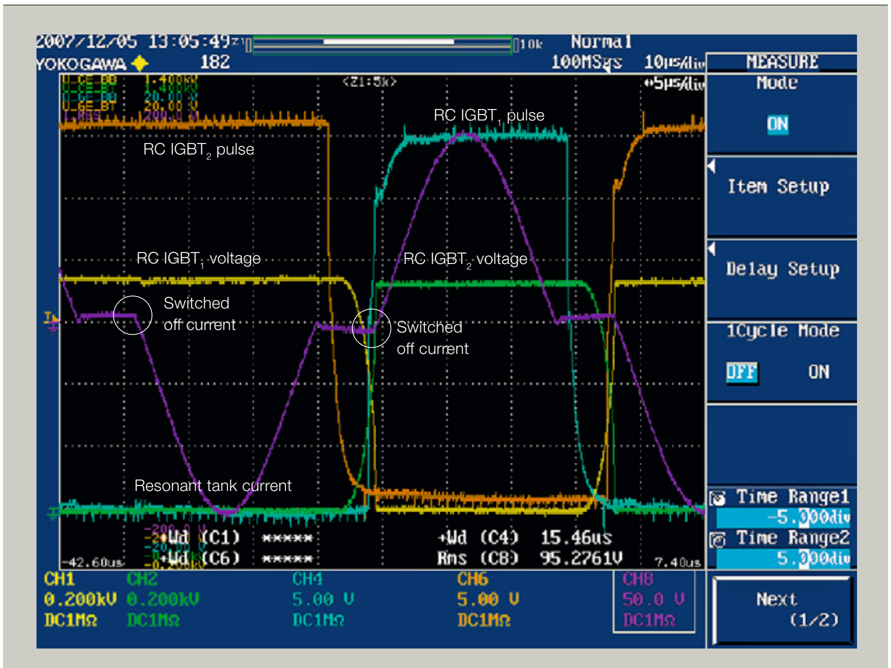
Resonant converter control

With the input converter voltage already stabilized by the input PFC boost stage, the control technique adopted for the resonant stage is quite simple. The converter will in fact always operate in one single point regardless of the line-input voltage variation. Thanks to the function of the transformer's magnetizing current, the converter behavior will be load-independent. Furthermore, the switching functions of the devices of the three-level DC/AC converter in 9 are shifted by 180° by means of the interleaved modulation scheme: The equivalent frequency seen by the resonant tank passive elements is double the switching frequency of the silicon device. In particular, in the BORDLINE M series all the passive elements of the resonant tank are designed for a main frequency of 15 kHz, while the silicon devices are switched at half the value (7.5 kHz) 11.

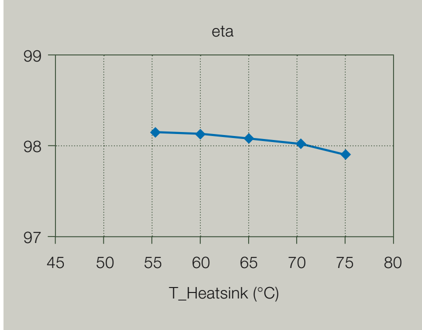
All the switching losses of the second converter stage are basically reduced to zero, highly enhancing the overall converter efficiency.

One of the most important issues related to resonant converters lies in the robustness of the system in the face of variations of parameters of the passive components. It was therefore necessary to evaluate how the con-

13 Resonant stage behavior



14 Resonant converter efficiency for different heatsink operating temperatures



verter losses were affected by such variations and whether proper ZVS and ZCS could still be guaranteed. 10 shows the diagram of the IGBT's "mean losses per cycle" obtained by simulations using Simetrix®. The diagram shows that fixing, for example, the resonant frequency at 15 kHz (as in this application), it is possible to limit the mean losses per cycle for each IGBT of the resonant DC/DC converter, even if the switching frequency is varied by up to 20 percent from its designed value. In the real world application, switching frequency is stable over time, but the resonant tank frequency may vary due to component tolerances, temperature and aging. Thanks to the effect of the transformer magnetizing inductance, the converter behavior is insensitive to load or system-parameter variations. Problems would have occurred, for example, if the resonant tank would be driven above the resonant frequency. In this case, ZCS operation mode would be lost.

Experimental results

The experimental results obtained during converter tests on the new BORDLINE M series 12 are presented in 13 and 14. In particular, the converter efficiency investigation has been conducted considering several operating points in the whole input voltage range of 700 Vrms to 1,300 Vrms and for different heatsink temperatures.

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References

[1] **Steigerwald, R.** (1988, April). A comparison of half-bridge resonant converter topologies. *IEEE Trans. on Power Electronics 3(2)*, 174–182.
[2] **Sabate, J., Lee, F.** (1991, January). Off-line applications of the fixed-frequency clamped-mode series resonant converter. *IEEE Trans. on Power Electronics, 6*, 39–47.
[3] **Raju, G. and Doradla, S.** (1995, March). An LCL resonant converter with PWM control – analysis, simulation, and implementation. *IEEE Trans. on Power Electronics, 10(2)*, 164–174.
[4] **Nomura, Y.** (2002, May 14). Power supply device for electromotive railcar. U.S. Patent No. 6,388,904 B2.
[5] **Rieux, O., Ladoux, P., Meynard, T.** (1999). Insulated DC to DC ZVS converter with wide input voltage range. *EPE Proceedings*.

Further reading

Lazar, J. F., Martimelli, R. (2001). Steady-state analysis of LLC series resonant converter. *IEEE APEC Rec.*, 728–735.
Yang, B., Lee, R., Chen, et al. (2001). LLC resonant converter for front-end DC/DC converter. *CPES Seminar Rec.*, 44–48.
Canales, F., Barbosa, P., Burdio, J., Lee, F. C. (2000). A zero voltage switching three-level DC/DC converter. *IEEE Intelec Rec.*, 512–517.
Canales, F., Barbosa, P., Aguilar, C., Lee, F. C. (2003, June 15-19). A high-power-density DC/DC converter for high-power distributed power system. *IEEE 34th Annual Power Electronics Specialists Conference*, Acapulco, Mexico, 11–18.
Barbosa, P., Canales, F., Jeon, S.-J., Lee, F. C. (2002). Three-level front-end converter for distributed power systems. *EPE-PEMC Rec*.
Gu, Y., Hang, L., Chen, U., et al. (2005). A simple structure of LLC resonant DC-DC converter for multi-output applications. *20th Annual Meeting of Applied Power Electronics Conference, 3*, 1485–1490.
Coccia, A., Canales, F., Barbosa, P., Ponnaluri, S. (2007). Wide input voltage range compensation in DC/DC resonant architectures for on-board traction power supplies. *EPE 2007*, Aalborg, Denmark.